Kinetic SZ effect and CMB polarization from subsonic bulk motions of dense gas clouds in galaxy cluster cores

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ABSTRACT

Recent *Chandra* observations have revealed the presence of cold fronts in many clusters of galaxies. The cold fronts are believed to be produced by the bulk motions of massive, dense, cold gas clouds with respect to the hotter, more rarefied ambient gas at velocities that can be as high as the speed of sound. This phenomenon may produce a significant contamination of both the kinetic SZ effect and the CMB polarization pattern observed in the direction of a cluster. We estimate the contributions to the kinetic Sunyaev-Zel'dovich (SZ) effect and to the CMB polarization toward galaxy clusters produced by the bulk motions of the gas in the inner parts of galaxy clusters. The observed cold fronts probe the absolute velocities of the gas motion while the induced polarization and the kinetic SZ effect probe the transverse and the radial components, respectively. We show that these signals may be easily detected with sensitive future experiments, opening an exciting new window for studies of galaxy cluster internal dynamics, and eventually facilitating reconstruction of the intrinsic cluster polarization of the CMB and the associated measure of the local CMB quadrupole.

Subject headings: submillimeter — cosmic microwave background — X-rays: galaxies: clusters — intergalactic medium

1. Introduction

Recent observations with *Chandra* have unveiled the presence of cold fronts in many galaxy clusters (Markevitch et. al. 2000; Vikhlinin, Markevitch, and Murray 2001, Mazzotta et. al 2001;

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Markevitch et al. 2002). The cold front is a discontinuity in the gas density and temperature characterized by the fact that the denser region is significantly colder than the rarefied component (thereby producing a pressure jump which is smaller than either the density or the temperature jump). Although the first cold fronts were discovered in merging clusters, *Chandra* later revealed the presence of cold fronts in many apparently relaxed clusters (e.g. Mazzotta et al. 2001; Markevitch et al. 2001; Mazzotta, Edge, and Markevitch 2003). Furthermore, a preliminary analysis shows that 2/3 of a X-ray flux limited sample of clusters of galaxies host cold fronts (Markevitch, Vikhlinin, Forman 2002). Since due to projection effects, only $\approx 1/3$ of all cold fronts can be observed in X-rays (Mazzotta et al. 2001), this strongly indicates that essentially all clusters of galaxies (including the most relaxed ones) host at least one cold front.

The most likely explanation for the presence of a cold front is that the cluster hosts a dense cold gas cloud which is moving with respect to the hotter and more rarefied ambient gas (Vikhlinin, et al. 2001). So far it is not completely clear why so many clusters (especially rounder, relaxed clusters) host moving gas clouds. One possibility is that the gas cloud in the central region is oscillating (sloshing) around the minimum of the cluster potential well (see. e.g. Markevitch et al. 2001; Markevitch et al. 2002; Mazzotta et al. 2003). This bulk gas motion may either be the result of a recent merger or due to dynamic feedback from the central (not necessarily currently active) AGN.

An important outcome of the study of cold fronts is that the gas thermal pressure at the front can be used to estimate the speed of the moving gas cloud (Vikhlinin et al. 2001). Preliminary studies have already revealed that these moving gas clouds have a wide range of sizes and velocities. More specifically: i) the size of the moving gas cloud can be as large as twice the cluster core radius; ii) the velocity is generally subsonic or at most transonic in rounder systems (e.g A1795, Markevitch et al. 2001; RXJ 1720+26, Mazzotta et al. 2001; 2A 0335+096, Mazzotta et al. 2003) and can be even supersonic in merger systems (e.g. A3667 Vikhlinin, et al. 2001; 1E 0657-56, Markevitch et al. 2002). It is interesting that the bulk motions, combined with the higher densities, of these gas clouds may induce a kinetic SZ effect as well as the polarization of the CMB. In this Letter, we study the contributions to the kinetic Sunyaev-Zel'dovich (SZ) effect and to the CMB polarization toward galaxy clusters produced by the bulk motions of these moving gas clouds in the inner parts of galaxy clusters.

2.   Kinetic SZ effect and polarization signals

The kinetic SZ effect is a distortion of the CMB spectrum due to the peculiar motion of the cluster with respect to the Hubble flow. This distortion is given by the expression,

$$\frac{\Delta T}{T} = -\frac{v_r}{c}\tau \equiv -\frac{v_r}{c}\int \sigma_T n dl \tag{1}$$

where v_r is the radial component of the velocity of the cluster, τ the optical depth of the cluster, σ_T the Thomson cross-section, and n the cluster gas density. This distortion is the same at all frequencies. The same CMB photons which undergo Compton scattering will be polarized after the scattering. The net polarized signal is proportional to the quadrupole of the incoming radiation (Rees 1968, Polnarev 1985). If the cluster is moving with a given velocity with respect to the Hubble flow, there will be an induced quadrupolar signal (Zel'dovich & Sunyaev 1980).

$$P = \frac{\sqrt{Q^2 + U^2 + V^2}}{I_{tot}} = 0.1 f(x)\left(\frac{v_t}{c}\right)^2\tau \tag{2}$$

where I_{tot} is the total intensity of the radiation, Q, U, V are the other Stokes parameters ($V = 0$ for Thomson scattering), v_t is the tangential component of the peculiar velocity of the cluster (cluster velocity projected on the sky plane) and $f(x)$ is the frequency dependence of the polarized signal (Sazanov & Sunyaev 1999),

$$f(x) = \frac{x^2 e^x (e^x + 1)}{2(e^x - 1)^2} \tag{3}$$

with $x \approx \nu(GHz)/56.8$. The resulting polarization plane is perpendicular to the velocity vector. As noted in Sazanov & Sunyaev (1999), there are other sources of CMB polarization in galaxy clusters. One of the most important is due to the intrinsic quadrupole of the CMB. For the COBE quadrupole, they estimated that the maximum signal should be $\approx 5\tau\ \mu K$ (Rayleigh-Jeans) which for typical cluster optical depths gives $\approx 10\ nK$. As we will see later, this value is comparable to the contribution of the cluster peculiar velocity plus the bulk motion of the central region. There are other mechanisms producing polarisation in the cluster but they have been discussed elsewhere (finite optical depth: Sazanov & Sunyaev 1999; cluster rotation: Chluba & Mannheim 2002).

3.   Cold fronts: A toy model

Studies of cold fronts in clusters of galaxies have shown that many (if not all) clusters of galaxies host dense, cold gas clouds that move with respect to the cluster itself. These gas bulk motions may affect both the intrinsic kinetic SZ and the CMB polarization signal induced by the cluster. To predict the strength of the signal we make very simple assumptions using a toy model

to describe the dynamics of the cold fronts observed in the X-rays. The basic elements of our toy model are the cluster within which is embedded a dense gas cloud. To fully define the model, we only need to establish the *geometry* and its *dynamics*.

We define the geometry by assuming that both the cluster and the moving gas cloud have spherical symmetry. To maintain the spherical symmetry of the problem, we also assume that at the time of observation, the center of the moving gas cloud and the cluster center coincide. The displacement of the moving cloud with respect to the cluster center is discussed later. In accordance with observations, we assume that the cluster gas density profile is described by a β-model with $\beta = 2/3$ (Jones & Forman, 1999) that we truncate at the virial radius r_v: $n(r) = n_0/(1 + (r/r_c)^2)$. In the previous equation, r_c is the cluster core radius and n_0 is the central gas density that we obtain after fixing the total mass (and baryon fraction) of the cluster. For convenience, we assume that the virial radius and the core radius of the cluster are related by $p = r_v/r_c$, with $p = 10$. In the same way we parameterize the real size of the moving gas cloud r_T as $s = r_T/r_c$ and we take the same central density n_0 (although other values could be considered).

The dynamics of the model are defined by assessing the velocity of the gas at each point of the plasma. In our toy model, we simply assume that the cluster is moving with its own peculiar velocity $\vec{v}_1$ while the central gas cloud has a bulk motion $\vec{v}_2$ with respect to the cluster itself. It is convenient to parametrize the gas cloud velocity as $\vec{v}_2 = M v_s \hat{n}$, where M is the Mach number, v_s is the cluster speed of sound, and $\hat{n}$ the gas cloud direction of motion. It is important to note that while $\vec{v}_1$ is directly referred to the Hubble flow, $\vec{v}_2$ is given in the framework in which the cluster is at rest. Therefore, to obtain the final velocity of the moving gas cloud with respect to the Hubble flow, we need to add $\vec{v}_2$ to $\vec{v}_1$.

With this simplistic description it is easy to reduce the problem to a two-phase plasma with a discontinuity in the velocity. From Eqs. 1 and 2, we see that the signal (kinetic SZ and/or polarization) at any point of the cluster can easily be computed as: $S = (\tau_{cluster} - \tau_{cloud})g(\vec{v}_1) + \tau_{cloud}g(\vec{v}_1 + \vec{v}_2)$ where $\tau_{cluster}$ and τ_{cloud} are the optical depths of the entire cluster and the moving gas cloud respectively and we introduce the new function $g(\vec{v})$ which is $g(\vec{v}) \propto v_r$ and $g(\vec{v}) \propto (v_t^2)$ for the kinetic SZ effect and CMB polarization, respectively. We can also define the percentile variation

$$\Delta S_0/S_0 \equiv (S - S_0)/S_0 = \frac{\tau_{cloud}}{\tau_{cluster}} \frac{\Delta g(\vec{v}_1, \vec{v}_2)}{g(\vec{v}_1)} \qquad (4)$$

where $S_0 \equiv \tau_{cluster} g(\vec{v}_1)$. Using our toy model we can calculate τ_{cloud} and $\tau_{cluster}$ as a function of the angular distance θ from the cluster center. The gas cloud optical depth is given by:

$$\tau_{cloud} \equiv \tau(\theta, s) = \frac{2 n_o r_c \sigma_T}{\sqrt{1 + (\theta/\theta_c)^2}} \tan^{-1}\left[\sqrt{\frac{(s)^2 - (\theta/\theta_c)^2}{1 + (\theta/\theta_c)^2}}\right], \qquad (5)$$

where σ_T is the Thomson cross-section and θ_c is the angular dimension of the core radius. In

the same way, $\tau_{cluster}$ can be obtained from the previous expression by substituting $s = p$. We can illustrate the relative importance of the gas cloud in the center of the cluster by calculating the ratio: $\tau_{cluster}/\tau_{cloud} \approx 2$ This is particularly important as it tells us that, despite the small size of the cloud ($\approx 2.5\%$ of the total mass), the optical depth of the central moving gas cloud in the cluster center is comparable to that of the remaining part of the cluster ($\tau_{cloud} \approx \tau_{cluster} - \tau_{cloud}$). The above ratio can change for different models but for reasonable models it is close to 2. We can see that, in this case, the percentile variation of the signal in the innermost cluster region is approximately half of the percentile variation of the function g. As an example, let us consider $T = 9\,\mathrm{keV}$. Typical velocity values for such a cluster are $|\vec{v}_1| = 300\mathrm{km\,s}^{-1}$ and $|\vec{v}_2| = 1500M\,\mathrm{km\,s}^{-1}$. For convenience, we assume that i) the gas cloud moves at the sound speed ($M = 1$); ii) the direction of motion of the cluster and the central cloud form angles of $45°$ with respect to the line of sight (in such a way $v_r=v_t$ and both the cluster and the moving cloud contribute to the kinetic SZ effect and the CMB polarization); iii) the direction of motion of the cluster is in the y-z plane while the direction of motion of the the central cloud is in the x-z plane (the z-axis is aligned with the line of sight). In this simple situation for the kinetic SZ effect, we find that $\Delta g(\vec{v}_1, \vec{v}_2)/g(\vec{v}_1) = 5$. This means that because of the moving dense gas cloud, in the innermost cluster region, the SZ effect induced by this cluster is $\approx 250\%$ higher than in the "classical" case in which such a motion is not taken into account. If we calculate the polarization, the effect is even more dramatic since the signal is proportional to the square of the velocity. In particular $\Delta g(\vec{v}_1, \vec{v}_2)/g(\vec{v}_1) = 26$, which means that the polarization effect is $\approx 1300\%$ higher! Interestingly, due to the dependence on the square of the velocity, the polarization signal is insensitive to the sign of the velocity. Two regions having velocities with opposite sign (but the same magnitude) will contribute similarly to the polarization. Therefore, a cancellation of the polarization signal through averaging the signal over the cluster is less likely than in the case of the kinetic SZ effect (unless the velocities are orthogonal, in which case they produce a cancellation in the polarization).

To better illustrate the contribution of the gas cloud to the SZ effect and CMB polarization, we show in Fig. 1 the maps of these signals induced by the toy model described above. In these maps, the gas cloud is displaced from the cluster center by 60 kpc in both x and z directions. Such a displacement is seen in many round clusters with cold fronts (e.g. A1795, 2A 0335+096, RXJ1720+26) consistently with the fact that the central cluster region is moving with respect to the cluster. Clearly, the displacement of the moving region introduces an asymmetry into the previous problem making it rather more complicated to interpret. The figure shows an evident enhancement of both the kinetic SZ effect and CMB polarization over the entire region corresponding to the size of the moving cloud. For clarity in the figure, we also show the kinetic SZ effect along a linear scan crossing the center of the cluster of the toy model (continuous line) and the same signal corresponding to a model with no moving gas cloud (dashed line). We notice that i) the peak of the signals are shifted which is a simple consequence of the dispacement of the moving gas cloud; ii) the SZ signal of our toy model is ≈ 3 times higher than the "classical" signal for most of the

cluster region corresponding to the size of the moving cloud. For the CMB polarization we find that the maximum amplitude signal for the toy model is 340 nK (at 300 GHz). In the Rayleigh-Jeans regime, this amplitude drops to 23 nK. This number is comparable to (or even higher than) the estimated amplitude of the polarization from the local CMB quadrupole (Sazanov & Sunyaev 1999). The maximum polarization signal can be compared with the expected maximum signal in the classical case (no moving cloud), 25 nK (300 GHz).

To conclude the description of our toy model, in Fig. 2 we show the SZ effect and CMB polarization maps in the case in which the direction of motion of the cluster is opposite to that of the gas cloud. We notice that with respect to the other case considered, the amplitude of the polarization is smaller. This is simply due to the fact that the velocity of the cluster partially compensates the velocity of the moving clouds. Much more interesting, however, is the signature of the kinetic SZ effect. It shows a unique feature: a positive peak in the middle of the negative well. This feature can be used in high resolution, high sensitivity experiments to unequivocally identify bulk gas motions inside clusters of galaxies.

4.   Discussion and Conclusions

In the previous section, we showed that the bulk motion of a dense gas cloud in the cluster center may significantly affect both the kinematic SZ effect and the CMB polarization signal induced by clusters of galaxies. On the one hand, this effect represents a strong source of noise for all experiments that require a precise measurement of the SZ effect and cluster-induced CMB polarization. On the other hand, it provides a new tool to better investigate the cluster structure. In the following we discuss these two aspects.

4.1.   Bulk gas motion as a possible source of noise

Peculiar velocities of galaxy clusters are an important cosmological tool since they can be connected with the velocity field of density perturbations (see e.g Chiu et al. 1998, Colberg et al. 2000, Sheth & Diaferio 2001). The kinematic SZ effect is thought to be one of the most promising mechanisms for measuring these peculiar velocities (e.g Haehnelt & Tegmark 1996, Holzapfel et al. 1997, Aghanim et al. 2001).

In a similar way, the measurement of the CMB quadrupole in different areas of the universe may be the only way to solve such questions as whether or not we live in a universe with a particularly low quadrupole or we live in a universe with a peculiar geometry (Kamionkowski and Loeb 1997) or we are seeing a possible signature of new physics (e.g Efstathiou 2003, Cline et al. 2003, Feng & Zhang 2003). The measurement of the polarization signal (due to the CMB quadrupole) in galaxy
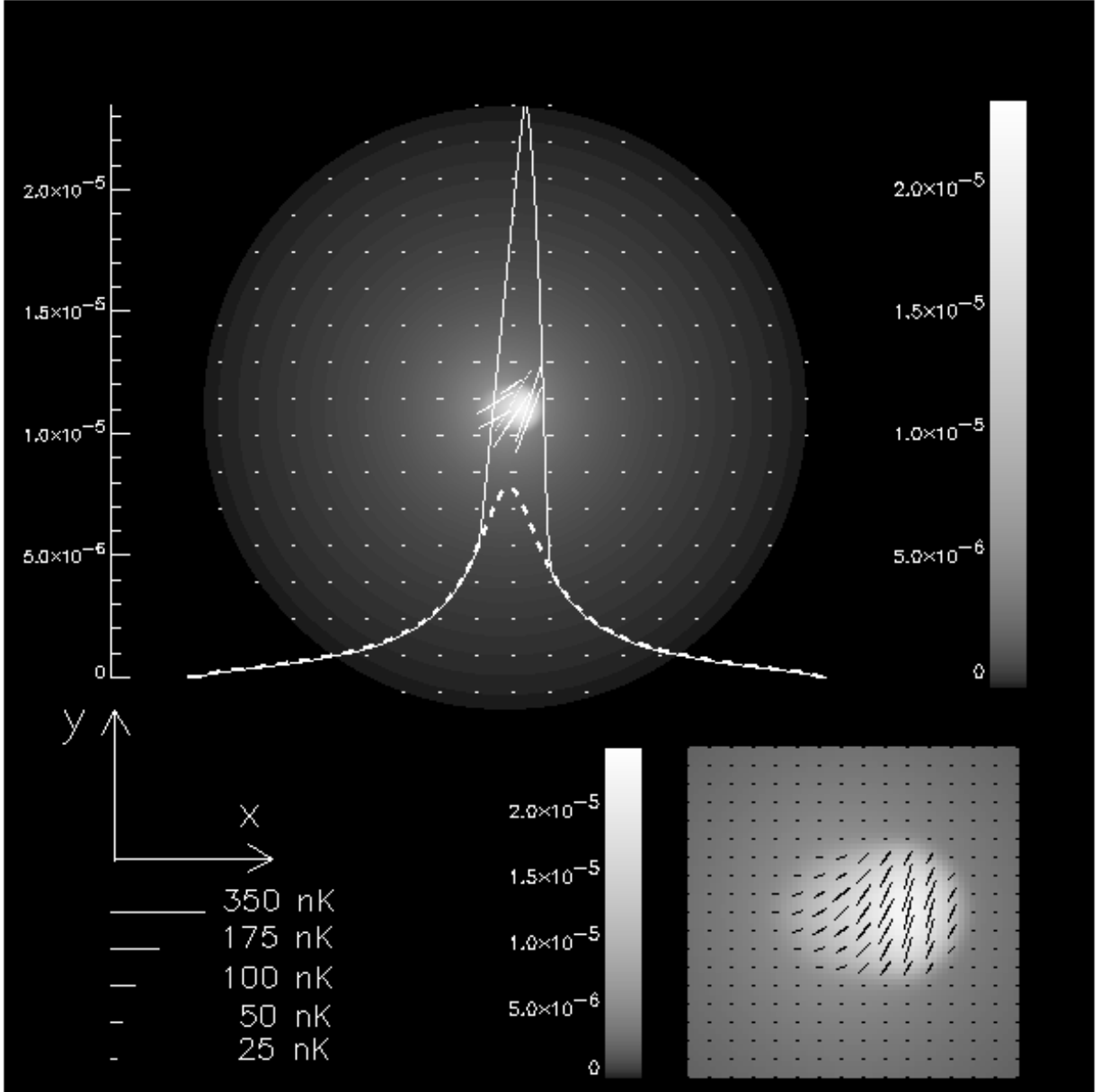
Fig. 1.— Kinetic SZ effect ($\Delta T/T$, gray scale) plus polarization signal (short lines) for the case where the central core and the cluster have positive velocity along the line of sight. In both cases we have assumed that the velocity vectors form 45° with the line of sight so the cluster and central region contribute to both polarization and kinetic SZ effect. Moreover, we assume that the cluster

clusters can also be used as a probe of the dark energy which would boost the CMB quadrupole by the integrated Sachs-Wolfe effect (Cooray & Baumann 2003).

The bulk gas motion can represent a serious issue for all the proposed cosmological studies devoted to measuring the peculiar velocities of galaxy clusters including kinetic SZ and/or local CMB quadrupole measurements from polarization. In the case of the kinetic SZ, this problem is solved if one assumes that the total signal is still proportional to the total average momentum of the cluster. These studies can be also affected by other secondary effects such as the kinetic SZ effect and polarization associated with cluster rotation (Chluba & Mannheim 2002).
A way to circumvent this problem is by using data from high-resolution, high-sensitivity experiments which can disentangle the central from the external signal or by means of multifrequency observations which could disentangle the kinetic polarization term from the contribution due to the scattering of the CMB quadrupole. An estimate of the cluster velocity after averaging over the kinetic SZ map can produce unbiased estimates of the peculiar cluster velocity with a dispersion of 50-100 km s^{-1} when the velocities are averaged over an aperture at least as large as the virial radius (Nagai et al. 2003). Also, averaging the polarization measurements toward galaxy clusters in a region of the sky would help to reduce the contribution from the kinetic polarization term (Cooray & Baumann 2003). However, the number of clusters which need to be *averaged* will depend on the dispersion of the kinetic polarization term. The effect studied in this Letter will increase this dispersion.

4.2. A powerful new galaxy cluster investigation tool

One interesting aspect of the kinetic SZ effect and the CMB polarization is that while the first depends on the radial component of the velocity, the latter depends on the tangential component. Obviously the two measurements are complementary and can in principle allow us to fully reconstruct the 3D velocity vector. However, the signal we observe is a combination of the signal associated with the moving gas cloud and the cluster itself. Thus, the gas cloud velocity 3D reconstruction depends on the actual cluster and gas cloud density profile. A steeper profile will show more *contrast* between the central and external parts of the cluster while a shallower profile will show a smoother gradient in both the kinetic SZ and polarization 2D data. Fortunately, information about the optical depth can be easily obtained combining the thermal SZ effect ($\propto \tau T$) with the temperature information obtained from X-rays observations. Furthermore, the X-ray observations of the possible cold front associated with a moving cloud will give us the absolute velocity of the gas cloud. This is a good example of how multi-wavelength observations of the same object can
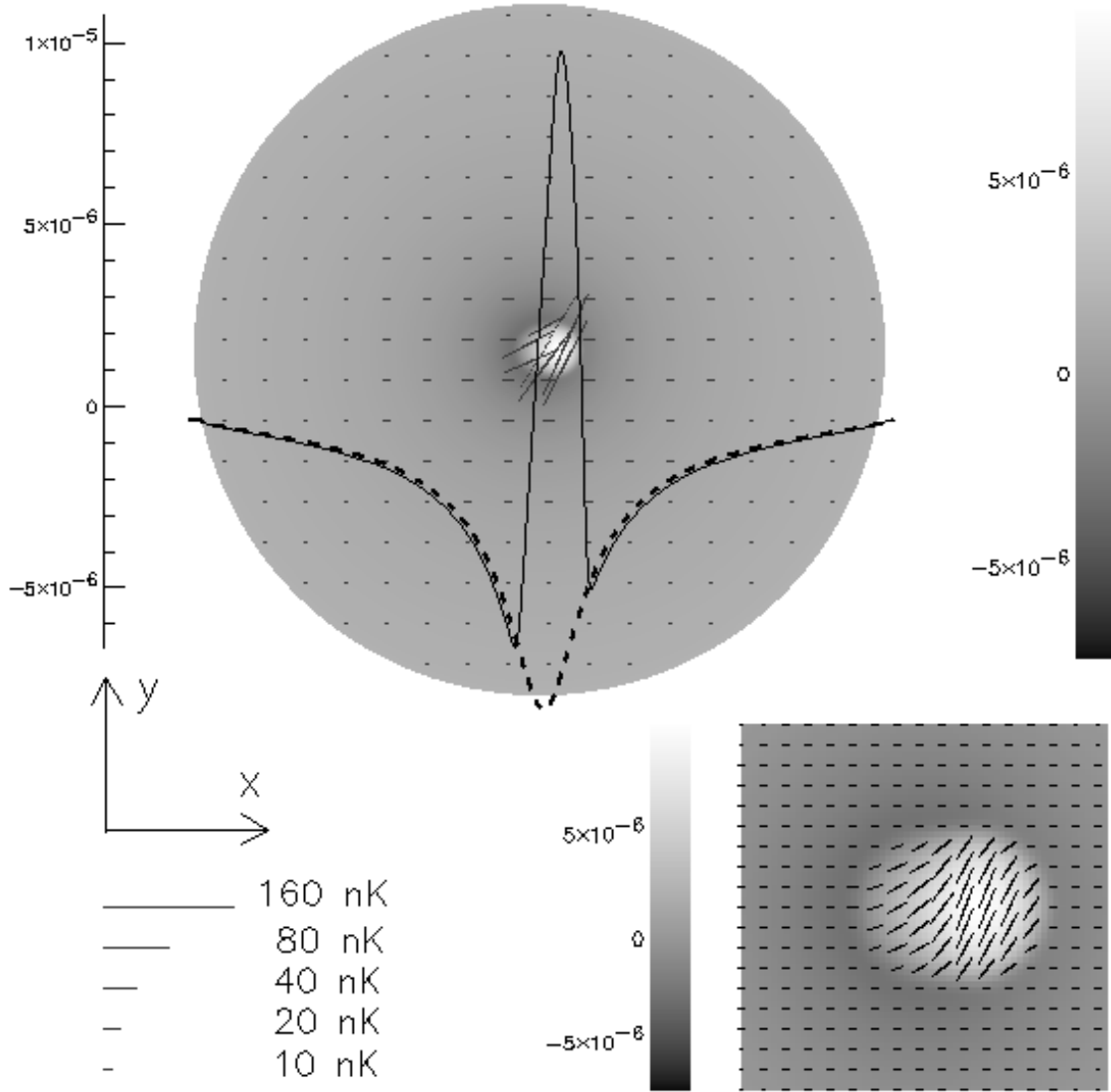
Fig. 2.— As in figure 1 but when the cluster has negative velocity along the line of sight ($v_1 < 0$). The amplitude of the polarization is smaller in this case because the negative velocity of the cluster partially compensates the positive velocity of the central region. The maximum polarization is ≈ 160 nK (300 GHz).

be used to reconstruct its 3D structure. In conclusion, it is clear that, future experiments having capabilities to measure the kinetic SZ effect and/or polarization of CMB photons induced by galaxy clusters with high spatial resolution will open new and exciting windows for the studies of galaxy cluster dynamics.

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